A Comparative Study of the Performance of Wood-Plastic Composites and Typical Substrates as Heating Floor

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The thermal properties of wood-plastic composites (WPCs) and typical heating floor substrates heated by an electrothermal film were studied. Their effects on human feelings and the human autonomic nerve system were also investigated. The temperature changes of the specimens during heating and cooling were analyzed with an infrared thermal imager. People's subjective feelings of touching different materials were analyzed with a semantic differential (SD) technique, and their electrocardiography was recorded with a multi-channel physiological signal acquisition system. The thermal conductivity, temperature variation, tactile impression, and heart rate variability of WPCs and other heating floor substrates were investigated. The WPCs presented a markedly lower thermal conductivity and superior tactile impression compared with ceramic tile, which has a similar density to WPCs. There was a negative correlation between the scores of the warm-cool feeling and the density of the heating floor substrates under room temperature (19 °C ± 1 °C), and a positive correlation when heated (33 °C ± 1 °C). The thermal conductivity and heat storage capacity of WPC were higher than those of solid wood. Electric heating composite floors with a high comfort level and good thermal properties could be manufactured by combining WPCs and solid wood.

Keywords: Heating floor; Wood-plastic composites; Thermal properties; Infrared thermal imaging; Building materials

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INTRODUCTION

A heating floor improves indoor comfort and can be used for the fast rebuilding of old houses. The heating location and heating power are adjustable, which helps reduce energy consumption (Qi *et al.* 2012). Compared with the heating pipes imbedded in floors or walls, heated floors provide a more flexible way of heating a certain area (Blomqvist 2008; Jin *et al.* 2010). Compared with other materials, wood-based materials are easy to manufacture. Their comfortability, pleasant appearance, and warm color are well accepted and favored for indoor use, and are they welcomed by the occupants of buildings (Kim *et al.* 2008; Ximenes and Grant 2013; Seo *et al*. 2014). These characteristics make wood-based materials promising candidates for high-performance heating floor substrates (Obata *et al.* 2005; Wastiels *et al.* 2012). The properties of different wood-based materials vary greatly, which makes their characterization necessary when finding the appropriate heating floor materials (Farag 2008; Fontana 2011; Guo *et al.* 2016).

The effects of different wood floor materials on the heat flux and surface temperature distribution have been studied using water-heating systems (Mi *et al.* 2015). When the thermal properties of four different wood veneers and the floorboards of three different structures were compared, solid wood of higher density was the most suitable for indoor heating (Chen *et al.* 2015). To improve energy-efficiency and find floor materials of better thermal conductivity, researchers using electrothermal films as a heat source have studied the thermal properties of floorboards prepared with solid wood and high density fiberboard and compared their heat transfer coefficients and heat storage properties (Seo *et al.* 2011). As a novel environmentally friendly building material, wood plastic composite (WPC), which is prepared with lignocellulosic fibers and thermoplastic polymers, has recently drawn increasing attention. There are several potentially advantageous characteristics when WPC is used for indoor decorations, including fire retardance, smoke inhibition, structure-strengthening, water proofing, decay resistance, and microbe inhibition (Ou *et al.* 2012; Yu *et al.* 2015; Huang *et al.* 2016). Studies of the life cycle, mechanical properties, and costs associated with WPC flooring compared with solid-wood flooring suggest that WPC has better weather resistance and durability than solid-wood flooring (Feifel *et al.* 2015). The above-mentioned studies do not address the feasibility of manufacturing WPC heating floors. However, they still provide a significant reference for manufacturing heating-material imbedded composite flooring and for improving the production efficiency and reducing costs, and their results support the feasibility of manufacturing WPC heating flooring. Although the thermal properties of WPCs and typical floor substrates have rarely been comparatively studied, their effects on the feelings and the physiological/psychological status of human subjects have never been reported. Studies on the thermal properties would provide an important reference for determining whether WPC is an appropriate substrate for heating floors and for the development of novel wood-based heating floors.

In the present study, the thermal properties of WPC board, solid wood board, plywood, fiberboard, and ceramic tiles were determined. The properties of different floor substrates during heating and cooling and after persistent heating were compared, and wood-based materials that presented superior properties were selected for further analysis. The potential application of wood-based materials in the manufacturing of heating floor is discussed. In addition, the cold/warm feelings and heart rate variability of human subjects when contacting different wood-based materials were quantitatively analyzed. The characterization of the thermal properties of materials and the analysis of the subjective feelings of human subjects provide references for the design and development of wood-based heating floors.

EXPERIMENTAL

Materials

Board specimens

Pinus sylvestris var. *mongolica* Litv. solid wood (SW) specimens were prepared on a rotary-cut board on a wood planer (5% to 8% moisture content). Plywood (PW) specimens were prepared from three-layer plywood, in which the veneers were laid interlaced (1.7 mm veneer thickness, 5 mm plywood thickness, 5% to 8% moisture content). Medium density fiberboard (MDF) specimens were cut from medium-density fiberboard (Nature Flooring Holding Company Limited, Shunde, China) using a panel saw.

The wood plastic composite (WPC) specimens were prepared from polypropylene (PP, type T30s, Daqing Petrochemical Co., Daqing, China), poplar wood flour (approximately 177 µm to 420 µm particle sizes), maleic anhydride grafted polypropylene (MAPP; type 9801, Shanghai Sunny New Technology Development Co. Ltd., Shanghai, China), and polyethylene wax at a weight ratio of 36:60:3:1. The ceramic tile (CT) specimens were prepared from ceramic tiles, which were sanded to 5 mm thickness and had smooth bottom surfaces. The dimension, density, and thermal conductivity of specimens of the five different materials are summarized in Table 1.

Table 1. Dimension, Density, and Thermal Conductivity of Specimens of Five Different Materials

Samples	Dimensions (mm^3)	Density (g/cm^{-3})	Thermal Conductivity* (W/mK)
SW	100 × 100 × 5 or 100 × 100 × 2	0.42	0.16
PW	100 × 100 × 5	0.54	0.23
MDF	100 × 100 × 5	0.81	0.23
WPC	100 × 100 × 5 or 100 × 100 × 2	1.28	0.31
CT	100 × 100 × 5	1.50	0.91

Adhesives

Two-part epoxy resin adhesives (epoxy resin and curing agent) (Shanghai Xiali decoration material Co. Ltd., Shanghai, China) were mixed at a ratio of 1:1 before use.

Heating material

The electrothermal films (0.34 mm thickness; World Electron, Kumchon-gu, Korea) consisted of polyester film, carbon fiber conductive ink grids, a copper electrode, and a conductive silver paste. The carbon fiber conductive ink grids, copper electrode, and conductive silver paste were placed between two layers of polyester films (Fig. 1a).

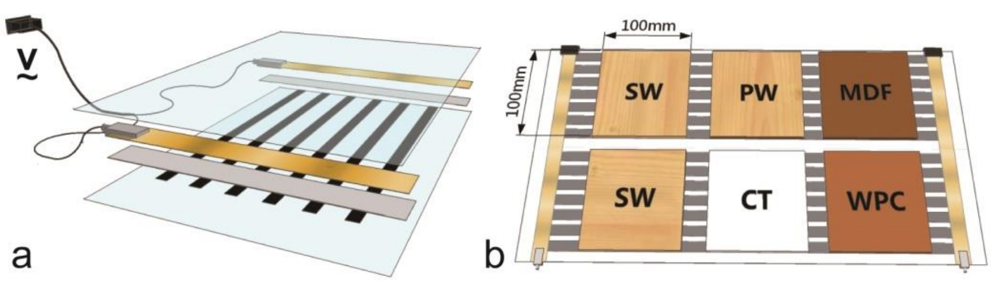

Fig. 1. Scheme showing (a) the structure of electrothermal film, and (b) the attachment of specimens to the electrothermal film

Equipment

A thermodetector (Benetech GM900, Jumaoyuan Science and Technology, Shenzhen, China) was used to measure the ambient temperature with a temperature range of -50 °C to 900 °C, a resolution of 0.1 °C, and an accuracy of ± 1.5 °C.

A thermal infrared imager (Ti200 9Hz, Fluke Corporation, Seattle WA, USA) was used in the temperature range of -20 °C to 650 °C and had a ≤ 0.075 °C sensitivity and ± 2 °C accuracy. It was used to determine the temperature changes of the specimens during heating and cooling.

A thermal conductivity meter (model FOX314, TA Instruments, New Castle, DE, USA) was used to test the thermal conductivity of specimens with the following parameters: hot wire measurement technique; conductivity, 0.023 W/mk^{-1} to 12 W/mk^{-1}; and ± 5% accuracy.

A multi-channel physiological signal acquisition system (RM6280C, Chengdu Instrument Factory, Chengdu, China) was used to monitor electrocardiography with the following parameters: input resistance of amplifier, ≥ 100 MΩ; common-mode rejection ratio, ≥ 100 dB; and input range, 5 μV to 250 mV.

Methods

Heating and cooling of electrothermal films

Strips of electrothermal film were connected to electrical power as shown in Fig. 1a. During the measurements, the electrothermal film strips were hung, and their temperature and the environmental temperature were recorded with the infrared camera. The emissivity was set at 0.95; the temperature range and level were set according to the environmental temperature. The copper electrodes of the electrothermal film were connected to 220 V of alternating current, and its surface infrared thermal images were recorded with the infrared thermal imager. After the temperature of the electrothermal film had reached a constant value, it was disconnected from the alternating current, and changes in its surface temperature were recorded until it reached room temperature. Nine replicates were investigated.

Heating and cooling of board specimens

The specimens were attached to the graphite electrothermal film with epoxy resin adhesives to ensure tight contact (Fig. 1b), and they were horizontally hung at 20 cm from the floor. The specimens/electrothermal films were connected to alternating currents and their heating and cooling processes were measured as stated above.

Warm/cold feelings of human subjects

According to previous reports, different materials could cause different warm/cold feelings to human subjects, even though they are at the same temperatures (Fenko *et al*. 2010; Fujisaki *et al.* 2015). Consequently, it was important to investigate the effects of different materials on the warm/cold feelings of human subjects touching heated and unheated heating floors. Subjects were randomly selected from the qualifying subjects (non-smokers, age 23 ± 3) in the Northeast Forestry University. There were 10 men and 10 women selected from 2000 qualifying candidates, and the experiments were conducted between 19:00 to 22:00 in a quiet environment of soft light and fresh air to prevent interference from extreme weather, talking, intense activity, the deep breathing of subjects, and other potential disturbances. Subjects were asked to touch heated (heating group) and room temperature (RT group) specimens, which had reached equilibrium temperature during electrothermal film heating and at room temperature, respectively.

The subjects' feelings when touching five different materials of the heating group and the RT group were collected with a semantic differential technique (SD). The subjects scored their warm/cold feelings from 1 to 5, which corresponded to "cold" and "hot," respectively (Shang *et al.* 2000; Desmet and Hekkert 2007).

Electrocardiography of human subjects touching heated wood-based materials

Subjects were asked to lie on their back, and their electrocardiography (ECG) was recorded by the multi-channel physiological signal acquisition system with limb leads (Biel *et al.* 2001; Ueno *et al.* 2007; Chi *et al.* 2010). Each subject was allowed to lie on his or her back and relax, and when the subject's ECG was stable at 5 min, the ECG signal was recorded as a blank control (Ctrl). Subjects were then asked to touch the heated specimens of four different materials with their hands, and their ECG was recorded for 5 min each. The ECG signals were analyzed using RM6280 physiological signal analyzing software (Version 4.7, Chengdu, China), and the heart rate variability (HRV) of the subjects was calculated.

The HRV analysis was conducted with time-domain methods and frequency-domain methods. The time domain methods gave indexes including mean heart rate (mHR), standard deviation of average NN intervals (SADNN), root mean square of successive differences (RMSSD), and triangular interpolation of NN intervals (TINN), which could indicate activities of the sympathetic and parasympathetic nervous system and the balance of the autonomic nervous system.

The frequency-domain methods give indexes including 5 min total power (TP), very low frequency (VLF), low frequency (LF), high frequency (HF), and low/high frequency ratio (LF/HF). The VLF, to some extent, indicates the status of thermoregulation and fluid balance; LF indicates the intensity of the sympathetic nervous system activity and is correlated with excitement and stress. LF/HF is an index showing the overall regulation of the cardiovascular system by the autonomic nervous system (Hejjel and Kellenyi 2005; Balocchi *et al.* 2006).

RESULTS AND DISCUSSION

Thermal Properties of Heating Floor Materials

The temperature changes of the electrothermal film during heating and cooling (environmental temperature 18 °C) were captured with an infrared thermal imager (Fig. 2). Upon being connected to the alternating current, the average temperature of the electrothermal film gradually increased and reached 36 °C at 150 s and presented no further increase during the following 150 s (Fig. 2a). This suggested that a maximum temperature was reached at 150 s. Electrical power was shut off after 300 s heating, and the decrease in the surface temperature of the electrothermal film was rapid at first and then slowed, almost reaching a plateau at approximately 400 s. This suggested that the temperature of the electrothermal film could drop from its maximum level to room temperature within 100 s.

The average surface temperatures of electrothermal-film-attached specimens are shown in Fig. 2b. Figs. 2c and 2d are the enlarged curves of Fig. 2b in the temperature ranges of 0 to 10 and 10 to 30 min, respectively. The rates of temperature rise of SW, PW, MDF, WPC, and CT were calculated from the slopes of the linear regions of corresponding curves, which were 2.65, 2.69, 2.01, 1.79, and 1.94 °C/min, respectively. The heat transfer coefficients were calculated as 0.16, 0.23, 0.23, 0.31, and 0.91 W/mK, respectively. Typically, materials that have larger heat transfer coefficients present faster increases in temperature. However, such correlations were not observed in the present study, which might be explained by the type, structure, and surface heat dissipation rate of the materials tested. SW, PW, MDF, and WPC are organic materials, while CT is an inorganic material. The cell structures in SW and PW were well retained, while they were not clearly so in MDF and WPC, despite the fact that the latter are also wood-based materials and contain micropores. In addition, WPC differs from other materials in density and porosity; most importantly, the polymer in WPC is a continuous medium, which greatly contributes to the differences in thermal properties between WPC and other materials. The equilibrium temperatures of the specimens were measured to be CT > WPC > PW > MDF > SW, which was consistent with the sequence of their heat transfer coefficients. Figs. 2e and 2f present the infrared images of the electrothermal film and samples at their maximum temperature.

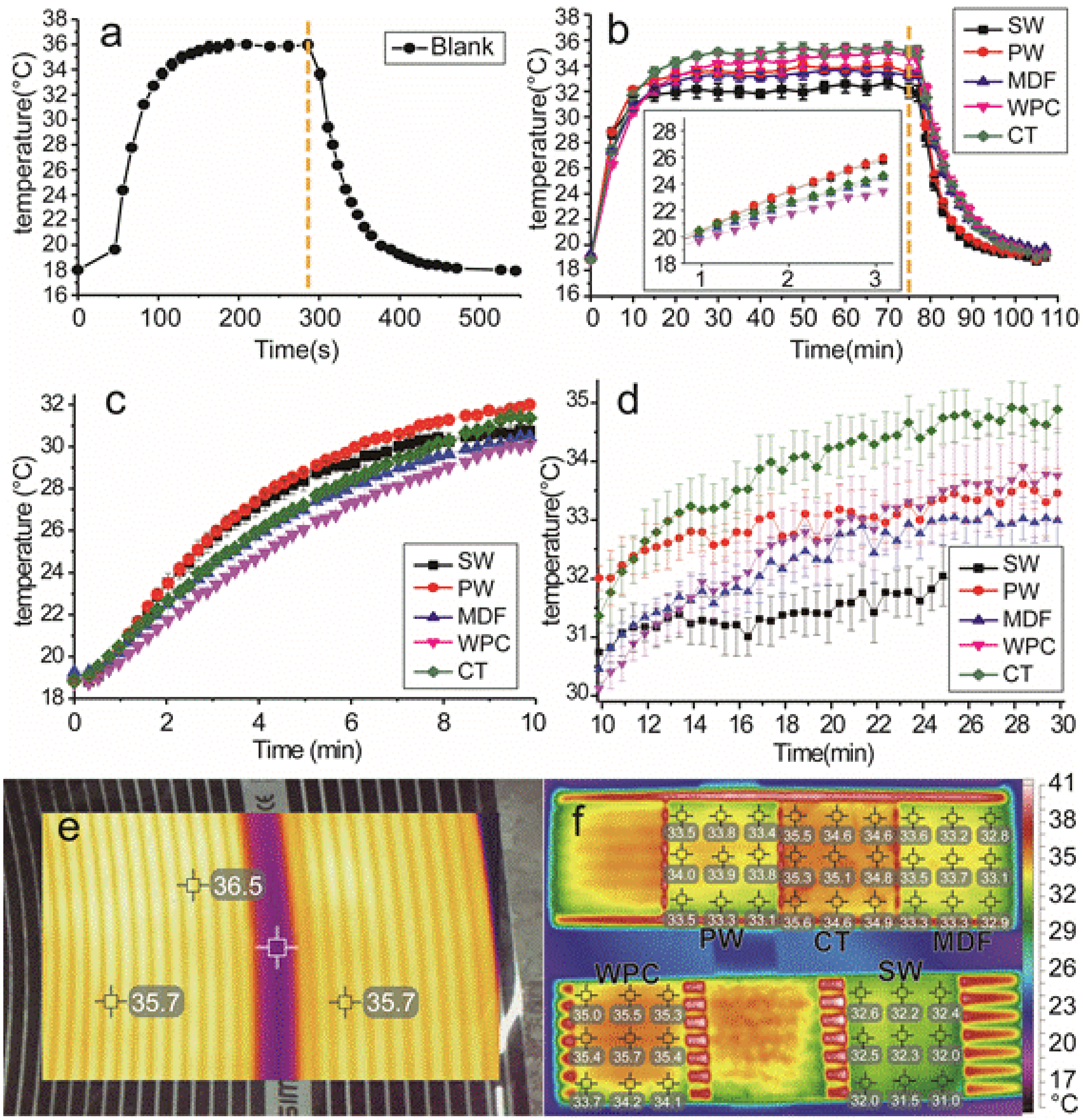

Fig. 2. Temperature changes of 5 mm-thick specimens during the heating and cooling processes: (a) temperature changes of the electrothermal film; (b) temperature changes of different materials; (c) temperatures of specimens in the first 10 min; (d) temperatures of specimens between 10 min and 30 min; (e) infrared image of graphite electrothermal film after 280 s of heating; and (f) infrared image of specimens after 75 min of heating

The differences between the equilibrium temperatures of the specimens' top and bottom surfaces (T_v) are shown in Table 2. Wood-based materials showed higher T_v values than the CT, and their sequence was SW > PW > MDF > WPC, which suggested the correlation between the density and the thermal conductivity of a material (Chen *et al.* 2015). The density of WPC could be manipulated by adjusting its recipe and processing techniques (Leu *et al.* 2012; Prisco 2014), so that the thermal conductivity of the WPC could be designed to meet the requirements for heating floor production. This makes WPC a promising material for making high-performance heating floors.

Table 2. Surface Temperature (T_s), Mean Surface Temperature (T_{up}), Bottom Temperature (T_b), and Difference between Equilibrium Temperatures of Top and Bottom Surfaces (T_v) of the Specimens (standard deviation in parentheses).

Samples	T_s (°C)	T_{up} (°C)	T_b (°C)	T_v (°C)
SW	16.8 (0.06)	31.5 (1.23)	35.9 (0.72)	4.4
PW	16.9 (0.04)	33.0 (1.06)	37.0 (0.24)	4.0
MDF	17.3 (0.14)	33.1 (0.53)	36.9 (0.38)	3.8
WPC	17.0 (0.12)	33.3 (1.82)	35.4 (0.51)	2.1
CT	17.0 (0.05)	34.7 (0.49)	35.9 (0.26)	1.2

The temperature changes of the specimens during the heating (measured every 5 min) and cooling (measured every 2 min) processes are shown in Tables 3 and 4, respectively. In the first 5 min of heating, the temperatures of the SW and PW specimens increased to 9.8 °C and 10 °C, respectively, faster than the specimens of the other materials (Table 3). However, between 10 min and 25 min, the temperatures of the other specimens increased faster than those of the SW and PW. The temperature of the SW specimens showed no further increase after 25 min and stayed at approximately 32 °C until the end of the heating process (55 min). The PW and MDF specimens presented no further increase in temperature after 30 min of heating, and stayed at about 34 °C. The temperature of the WPC continued to rise until 40 min, and then stayed approximately 35 °C afterwards. These results suggested the correlations between the thermal conductivity of these materials and their densities, and were consistent with their heat transfer coefficients at room temperature (Table 1).

Table 3. Surface Temperature Changes of Specimens during Heating

Samples	Temperature Change Every 5 min (°C)										
	5	10	15	20	25	30	35	40	45	50	55
SW	9.8	2.3	0.7	0.2	0.2	-0.2	0.0	-0.2	0.4	-0.2	0.4
PW	10.0	3.3	0.7	0.4	0.3	0.0	-0.1	0.1	0.1	0.4	-0.2
MDF	8.1	3.5	1.4	0.5	0.4	0.1	-0.1	0.0	0.1	0.1	0.2
WPC	7.4	4.1	1.9	0.8	0.6	0.4	0.0	0.3	-0.2	0.4	0.2
CT	8.6	4.2	1.9	0.7	0.5	0.3	-0.2	0.1	0.2	0.1	-0.2

Notes: The standard deviations of these values ranged from 0.08 to 0.4

During the cooling process (Table 4), the temperatures of the PW, SW, and CT specimens decreased faster than those of the MDF and WPC in the first 4 min. The temperature of the WPC specimens dropped more slowly than any of the other material tested, which suggested a slow, steady, and continuous temperature decrease.

In summary, the SW presented the best thermal insulation properties among the wood-based materials, as its temperature after ≥ 20 min of heating was remarkably lower than that of the other materials, and the WPC presented better thermal conductivity and slower cooling processes than the other materials.

Table 4. Surface Temperature Changes of Specimens during Cooling

Samples	Temperature Change Every 2 min (°C)												
	2	4	6	8	10	12	14	16	18	20	22	24	26
SW	-3.5	-3.6	-2.1	-1.3	-0.7	-0.5	-0.2	-0.2	-0.2	-0.2	0.0	-0.2	-0.1
PW	-4.1	-4.0	-2.1	-1.4	-0.8	-0.6	-0.4	-0.3	-0.2	-0.2	-0.1	-0.1	-0.1
MDF	-2.4	-3.1	-2.2	-1.4	-1.1	-1.1	-0.6	-0.4	-0.4	-0.3	-0.2	-0.2	-0.2
WPC	-2.3	-3.3	-2.1	-2.0	-1.1	-1	-0.9	-0.7	-0.5	-0.4	-0.3	-0.2	-0.3
CT	-3.6	-3.2	-2.2	-1.6	-1.2	-1.2	-0.8	-0.5	-0.5	-0.5	-0.2	-0.2	-0.2

Notes: The standard deviations of these values ranged from 0.04 to 0.6

Cold/Warm Feelings of Human Subjects when Touching Specimens Made of Different Materials

The cold/warm feelings of human subjects were collected and scored using the sematic differential technique (Table 5). At room temperature, most of the subjects regarded the CT as "cool" and the SW as "warm." When touching the heated specimens, the subjects reported that the CT felt "hot" while the SW felt "moderate." Subjects reported similar cold/warm feelings when they touched the other three wood-based materials, which were quantitatively between the SW and CT. By comparing results in Table 1 and Table 5, the authors summarized the correlations between the thermal properties of these materials and the cold/warm feelings of the human subjects when touching the specimens at 19 °C ± 1 °C or 33 °C ± 1 °C. The subjects' cold/warm feelings were correlated with the density and heat transfer coefficient of a material. The density of the materials and the cold/warm feelings of the subjects were negatively correlated at room temperature, while positively correlated when the specimens were heated. This is because heat flowed from the human bodies to the room-temperature specimens, so that the materials of higher density (and thus better thermal conductivity) felt cooler, while heat flowed from the heated specimens to human bodies, so that the materials of higher density (and thus better thermal conductivity) felt warmer.

Table 5. Scores of Subject's Cold/Warm Feelings when Touching the Five Different Materials (standard deviation in parentheses)

Group	SW	PW	MDF	WPC	CT
RT Group (≈19 ± 1 °C)	2.85 (0.37)	2.75 (0.44)	2.50 (0.60)	2.40 (0.50)	1.40 (0.50)
Heating group (≈33 ± 1 °C)	3.20 (0.41)	3.45 (0.51)	3.75 (0.44)	3.80 (0.70)	4.80 (0.52)

Scores: 1 cold, 2 cool, 3 moderate, 4 warm, and 5 hot

HRV Analysis of Human Subjects when Touching Specimens Made of Different Materials

The mean heart rates (mHRs) of the subjects touching the heated wood-based specimens were higher than their mHR when they were not touching any specimens (Table 6). Compared with the Ctrl, the subjects touching heated SW specimens presented noticeably lower SDANN, RMSSD, and TINN, which suggested that when touching the specimens, their autonomic nervous system activity was low, their parasympathetic nervous system dominated, and the subjects were at a resting state (Mizuno *et al.* 2014). Compared with SW, the heated WPC specimens caused a lower mHR, but a much higher SDANN, which suggested that the activity of the sympathetic nervous system contributed to homeostasis of the subjects during the period of touching.

Table 6. Time Domain HRV Analysis of Subjects Touching Four Different Materials in the Heating Group

Samples	mHR (bpm)	mRR (ms)	SDANN (ms)	RMSSD (ms)	TINN (ms)
Ctrl	70.63	856.82	80.69	54.66	43.45
SW	76.50	785.24	26.95	26.32	14.42
PW	73.19	825.70	74.11	30.96	23.39
MDF	74.81	807.96	71.37	30.96	23.32
WPC	71.62	847.21	93.78	52.21	42.32

The VLF of subjects was lower than 15% when they were touching the SW specimens, and their LF/HF at that time was lower than their LF/HF when they were not touching any specimens (Ctrl) (Table 7). This suggested that their thermoregulatory system was not in a very active state, and indicated that their temperature and tactile impression were more comfortable. The LF values of the subjects when touching all of the wood-based materials were low, which suggested that touching the specimens did not cause any stress in the subjects. The subjects presented relatively high LF/HF values when they were touching WPCs, suggesting an enhanced regulation of the cardiovascular system by the autonomic nervous system and increased activity of the parasympathetic nervous system.

Table 7. Frequency Domain HRV Analysis of Subjects Touching Four Different Materials in the Heating Group (the percent of the TP in parentheses)

Material	TP (ms^2)	VLF (ms^2)	LF (ms^2)	HF (ms^2)	LF/HF
Ctrl	3082	1920 (63%)	702 (23%)	431 (14%)	1.63
SW	295	39 (14%)	94 (33%)	155 (54%)	0.6
PW	2990	2475 (83%)	351 (12%)	157 (5%)	2.23
MDF	2621	2050 (78%)	405 (16%)	157 (6%)	2.58
WPC	4503	3012 (67%)	1180 (26%)	298 (6%)	3.96

Comparing the Thermal Properties of WPC and SW

The temperature changes of WPC and SW specimens during the heating and cooling processes are shown in Fig. 3. Compared with the 5 mm-thick specimens, the surface temperature of the 2 mm-thick specimens increased continuously throughout the heating processes, never reached an equilibrium temperature, and had larger variations, which suggested that thinner specimens had higher heat dissipation rates and lower heat storage capacities.

Both the 2 mm- and 5 mm-thick WPC specimens presented higher surface temperatures than SW after a certain period of heating (Figs. 3a, b), which may have resulted from the anisotropicity and porosity of SW. Solid wood contains cell lumens, and these void spaces inhibit thermal transfer. In contrast, the polymer makes the interior of the WPC more homogeneous and thus facilitates heat transfer. The better thermal conductivity of WPC may contribute to a higher surface temperature of heated floors.

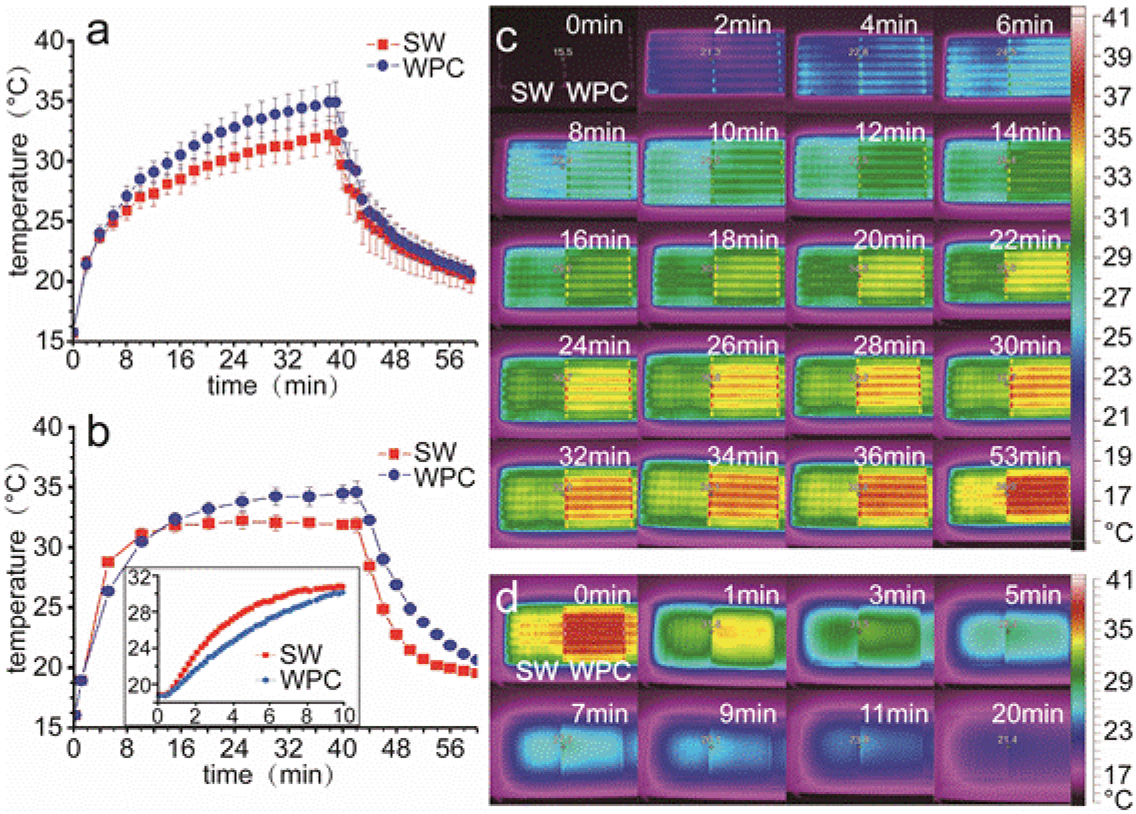

Fig. 3. Surface temperatures of WPCs and SW specimens: (a) temperature changes of 2 mm-thick specimens; (b) temperature changes of 5 mm-thick specimens; (c) Infrared images of 2 mm-thick specimens during heating; (d) Infrared images of 2 mm-thick specimens during cooling

During the heating process, the temperature of the environment also increased over time as a result of the heat transfer from the heated specimens (Figs. 3c, d). The average environmental temperature at 53 min, when the specimens reached the highest temperatures, was 18.3 °C, which suggested that rather than transferring to the surrounding environment, most of the heat transfer occurred inside the specimens. This is consistent with the basic law of heat transfer. Consequently, those heating boards would be more efficient in transferring heat to a human body when used as flooring rather than wall panels.

Surface temperatures of both the SW and WPC specimens started to decrease upon disconnection from the electric currents. Because the WPC had a higher starting temperature than the SW, the temperatures of the WPC were always higher than those of the SW during the cooling process, even though at later stages of the cooling process their differences got smaller. This suggested that the WPC specimens stored more heat than the SW specimens of the same volume.

The infrared images of the 2 mm- and 5 mm-thick WPC and SW specimens after being heated for 50 min and the temperature distribution curve of their diagonals are shown in Fig. 4. Both 2 mm- and 5 mm-thick WPC specimens showed a higher temperature than the SW specimens. After 50 min of heating, the average diagonal temperatures of the 2 mm-thick SW specimen (A line) and the WPC specimen (B line) were 32.8 °C and 35.9 °C, respectively, a difference of 3.1 °C. The average diagonal temperatures of the 5 mm-thick SW specimen (C line) and the WPC specimen (D line) were 32 °C and 34.5 °C, respectively, a difference of 2.5 °C.

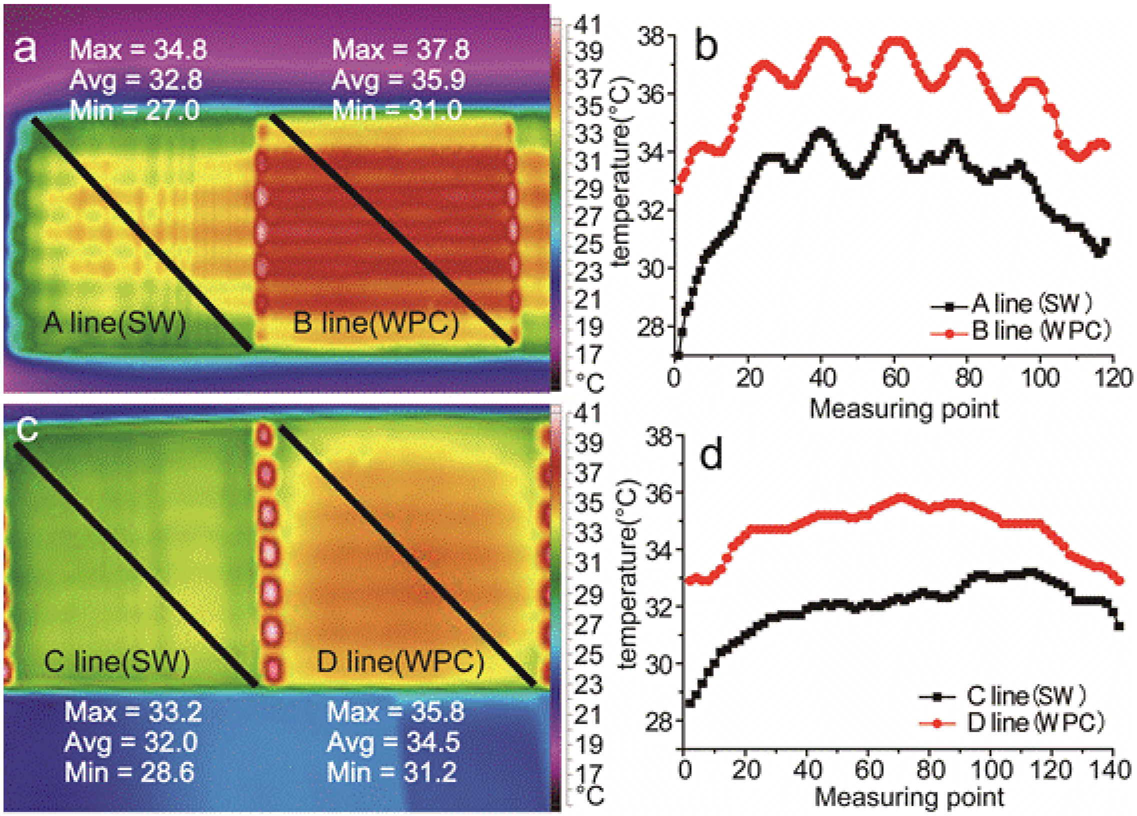

Fig. 4. Temperature distributions of WPC and SW after 50 min of heating: (a) Infrared images of 2 mm-thick specimens; (b) temperature distribution along A and B lines; (c) Infrared images of 5 mm-thick specimens; (d) temperature distribution along C and D lines

The surface temperature distributions of the two materials were consistent with the positions of the heating strips in the graphite electrothermal films, and such consistency was more obvious for the WPC and less obvious for the SW. The surface temperature of the 2 mm SW specimens was no higher than 35 °C, while WPC specimens of same thickness presented maximum temperatures over 37 °C. The corresponding temperature difference in the thicker (5 mm) specimens was smaller.

By comparing the infrared images with the surface grain distribution of SW specimens, the authors found that the surface temperature distributions of both the 2 mm and 5 mm SW specimens were affected by their grains. Consequently, to take advantage of the characters of both SW and WPC, a combination of the two materials should be considered in the research and development of heating floors.

CONCLUSIONS

1. The WPC had a higher density, heat transfer coefficient, and heat storage capacity than the PW, MDF, and SW. The thermal conductivity of each of these materials was positively correlated with its density.
2. The heated and the room temperature CT caused the most intense stimulation when touched by the human subjects. The stimulation caused by the WPC, PW, and MDF were less intense and the stimulation caused by SW was the weakest. According to the

time and frequency domain analysis of HRV, the SW affected the subjects' autonomic nervous systems most insignificantly among the tested materials, which suggested it was more comfortable than the others. A combination of WPCs and SW may contribute to the construction of a heated floor that is both comfortable and has better thermal properties.

3. By comparing the temperature changes of 2 mm and 5 mm WPC and SW specimens during the heating and cooling processes, the authors found that when heated to an equilibrium temperature, WPCs presented higher average temperatures than SW. Also, during the cooling process, the temperature of WPC specimens decreased slowly, steadily, and continuously, suggesting the better heat storage capacity of WPC compared to SW. These results provide a theoretical reference for developing WPC heating floors with better heat storage capacity.
4. Electric heating composite floors with a high comfort level and good thermal properties could be manufactured by combining WPCs and solid wood. Optimum structural design of the composite floors and their resistance to heat and humidity in practical application of architecture will be our future research.

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